The splitting of directed flow for identified light hadrons (K and p) and strange baryons (Ξ and Ω) in Au+Au collisions at STAR *

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The first measurements for rapidity-odd directed flow of Ξ and Ω in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 27$ and 200 GeV are reported. The coalescence sum rule is examined with various combinations of hadrons where all constituent quarks are produced, such as $K^{-}(\bar{u}s)$, $\bar{p}(\bar{u}\bar{u}\bar{d})$, $\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$, $\phi(s\bar{s})$, $\overline{\Xi}^{+}(\bar{d}\bar{s}\bar{s})$, $\Omega^{-}(sss)$, and $\overline{\Omega}^{+}(\bar{s}\bar{s}\bar{s})$. For such combinations, a systematic violation of the sum rule is observed with increasing difference in the electric charge and the strangeness content of the combinations. Measurements are compared with the calculations of A Multi-Phase Transport (AMPT) model and Parton-Hadron String Dynamics (PHSD) model with electromagnetic (EM) field. The PHSD model with EM field agrees with the measurements within uncertainties.

1. Introduction

Directed flow (v_1) is the first harmonic coefficient in the Fourier expansion of the final-state azimuthal distribution relative to the reaction plane. Theoretical calculations [1] based on nuclear transport and hydrodynamics indicate that the v_1 is sensitive to the early stages of the high energy heavy-ion collisions.

One of the most important features of the early stages of the heavy-ion collisions is the production of an extremely strong magnetic field due to the motion of the charged spectators. The produced magnetic field decays down fast since the charged spectators fly away from the collision zone and this generates an electric current in the plasma due to the Faraday effect. In addition, the plasma has a longitudinal expansion velocity along

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the beam direction and perpendicular to magnetic field direction, hence the Lorentz force pushes charged particles and anti-particles of the plasma in opposite ways which are perpendicular to both the directions of longitudinal velocity of plasma and the magnetic field. This is analogous to Hall effect. The charged spectators can also generate an electric current in the plasma due to Coulomb effect. The v_1 of different produced charged particles is greatly influenced by the resultant of Faraday, Hall, and Coulomb effects which eventually leads to the splitting of v_1 [2]. Both STAR and ALICE experiments measured a non-zero v_1 splitting with pseudo-rapidity between positively and negatively charged hadrons in Au+Au collisions at $\sqrt{s_{\rm NN}} =$ 200 GeV [3] and Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [4], respectively. However, the interpretation of the measured splitting using charged hadrons runs into difficulties especially when the effects of electromagnetic fields are concerned. This is due to the fact that among light hadrons, there are many (anti-)particles containing u and d quarks, which can be either transported from beam rapidity [5] or produced in the collisions. Due to the different number of interactions suffered, the transported u and d have different v_1 than those of the produced quarks [6]. This ensures a pre-existing splitting due to the transport. This transport driven splitting is a background in search of the pure electromagnetic-field-driven splitting. We could avoid the transported quarks in our analysis by selecting particles composed of produced constituent quarks only ($\bar{u}$, $\bar{d}$, s, and $\bar{s}$). The experimental method is outlined briefly in Sec. 2.

In this contribution, we report the measurements of v_1 of multi-strange baryons (Ξ and Ω). The v_1-splitting as a function of electric charge difference (Δq) and strangeness difference (ΔS) is measured, using K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^-, and $\overline{\Omega}^+$ from Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ and 200 GeV.

2. Data sets and Analysis strategy

STAR detector system is versatile experimental setup for track reconstruction, vertexing, and particle identification at RHIC. The main subdetectors are (i) Time Projection Chamber (TPC) ($|\eta| \leq 1$): used for charged particle tracking, vertexing, and particle identification; (ii) Time-Of-Flight (TOF) detector: used for particle identification; (iii) Event-Plane Detectors (EPDs) ($2.1 < |\eta| < 5.1$) and (iv) Zero-Degree Calorimeter with Shower-Maximum Detectors (ZDC-SMDs) ($|\eta| > 6.3$): can measure event planes of the collisions.

A high statistics data samples for Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ and 200 GeV are used in the measurements. We use events with the vertex position along the beam direction with $|V_{\rm z}| < 70$ cm, and along the radial directions, $V_r < 2$ cm at $\sqrt{s_{\rm NN}} = 27$ GeV; and $|V_z| < 30$ cm, $V_{\rm r} < 2$ cm at $\sqrt{s_{\rm NN}} = 200$ GeV. At the track level, $p_{\rm T} > 0.2$ GeV/c, and a distance of closest approach (DCA) from vertex, DCA ≤ 3 cm, and at least 15 space points in the TPC acceptance are selected. For particle identification, we use $p_{\rm T} > 0.2$ GeV/c, momentum < 1.6 GeV/c and $|n_\sigma| \leq 2$ for charged pions and kaons; $0.4 < p_{\rm T} < 5$ GeV/c, $|n_\sigma| \leq 2$ for p and $\bar{p}$, where n_σ is the standard deviation of difference between measured $\langle dE/dx \rangle$ and theoretical mean value for each particle type. The Λ, $\bar{\Lambda}$, Ξ^-, $\overline{\Xi}^+$, Ω^-, and $\overline{\Omega}^+$ are reconstructed using KF-Particle package [7]. The ϕ-mesons are reconstructed in K^+K^- channel using the invariant mass method with pair rotation background subtraction. The systematic uncertainties on the measurements are obtained by varying these analysis cuts. We remove the effect of the statistical fluctuations by employing Barlow's method [8].

The analysis method is based on the quark coalescence mechanism. Coalescence sum rule states that the directed flow of a hadron is consistent with the sum of the directed flow of its constituent quarks, *i.e.*, $v_1(\text{hadron}) = \sum\limits_i v_1(q_i)$, where the sum runs over the v_1 of the constituent quarks, q_i. There are many hadron species composed of constituent u and d quarks, which might or might not be transported from the incoming nuclei. The transported quarks produce background in search of the possible electromagnetic-field-driven v_1 splitting. Hence, in the analysis we take particles which contain produced quarks only, namely, $K^-(\bar{u}s)$, $\bar{p}(\bar{u}\bar{u}\bar{d})$, $\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$, $\phi(s\bar{s})$, $\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})$, $\Omega^-(sss)$, and $\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})$. All these particles have different flavour, electric charge (q) and mass (m); and v_1 is sensitive to quark flavour and mass. Keeping this in mind, we combine the different particles so that combinations have same or similar mass at the constituent quark level ($\Delta m \approx 0$), but $\Delta q \neq 0$ and $\Delta S \neq 0$. We found five independent combinations as shown in Table 1. The difference Δv_1 of such combinations is called "splitting of v_1" [9] and the slope of the Δv_1 vs. rapidity is a measure of the splitting. We measure the Δv_1 of all the indices in Table 1 to obtain the splitting as a function of Δq, a measure of EM-field-driven splitting. At the same time, we also measure the the Δv_1 with ΔS of all the combinations. Although, the change in Δq is also associated with a change in ΔS in Table 1 which comes from the quantum numbers carried by the constituent quarks.

3. Results and Discussions

Figure 1 displays the first measurements of Ξ and Ω baryon v_1 in 10%-40% central Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 200 GeV. We perform a linear fit, $v_1(y) = Cy$, where C is the fitting parameter, and y is the rapidity. We found: $C = -0.0083 \pm 0.0020$ (stat. $\pm\, 0.00$ (syst.)) $[-0.0148 \pm$

Index	Quark mass	Charge	Strangeness	Δv_1 combination
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
5	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

Table 1. Table showing difference in mass, charge, and strangeness between combinations formed from seven particle species composed of produced quarks only.

0.0028 (stat.)$\pm$0.0013 (syst.)] for Ξ^- $[\overline{\Xi}^+]$ and $C = -0.0214 \pm 0.008$ (stat.)$\pm$ 0.0034 (syst.) $[-0.0075 \pm 0.0118$ (stat.) $\pm$ 0.0017 (syst.)] for Ω^- $[\overline{\Omega}^+]$ at $\sqrt{s_{NN}}$ = 27 GeV. There is a hint of a larger v_1 for Ω^- compared to Ξ baryons is observed at $\sqrt{s_{\rm NN}} = 27$ GeV, though the uncertainties are large.

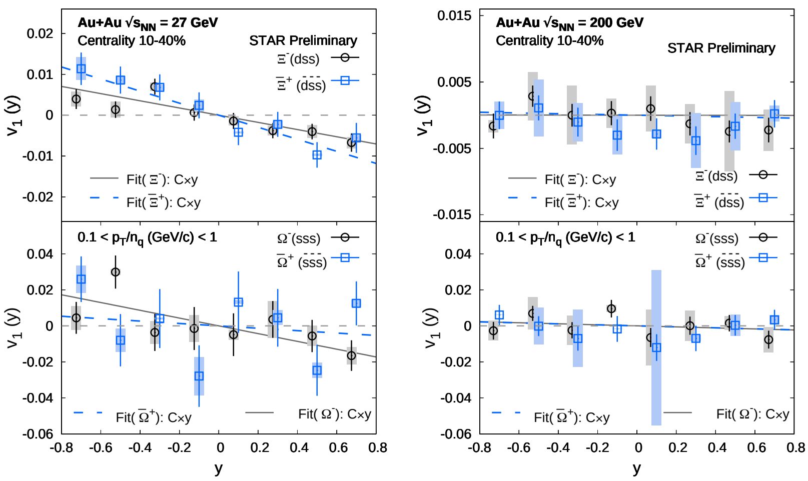

Fig. 1. v_1 of Ξ^-, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$ as a function of rapidity, y, in 10%-40% central Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ and 200 GeV.

In Fig. 2, we show the measured $\Delta v_1(y)$ for hadron combinations with $(\Delta q,\ \Delta S) = (0,\ 0)$, $(4/3,\ 2)$ in 10%-40% Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ GeV. The Δv_1-slope parameters of the measurements are extracted. For $\Delta q = 0$ and $\Delta S = 0$ (identical quark combination case), the value of the slope is a minimum compared to $\Delta q = 4/3$ and $\Delta S = 2$ cases. This minimum deviation from zero implies that the coalescence sum rule holds with the identical quark combination. The deviation of the slope from zero increases as we move to $\Delta q = 4/3$ and $\Delta S = 2$ case. A Multi-Phase Transport (AMPT) [10, 11] model calculation can describe the measured Δv_1 within errors for the $\Delta q = 0$, $\Delta S = 0$ case. For $\Delta q = 4/3$ and $\Delta S = 2$, AMPT depicts a completely opposite trend compared to the data.

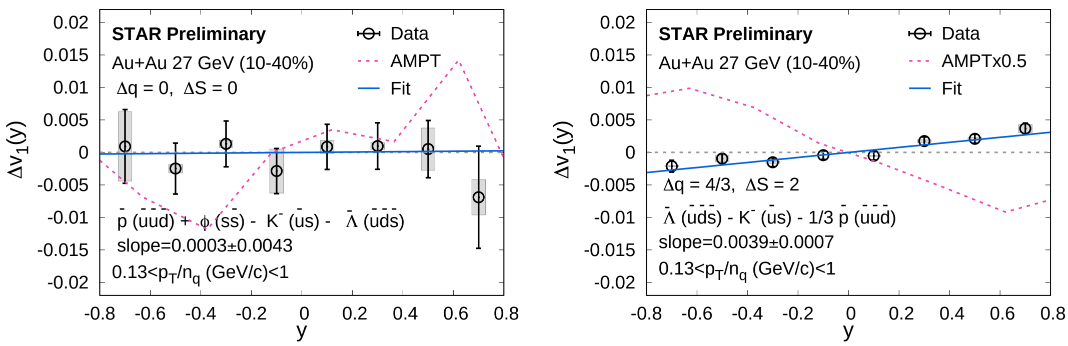

Fig. 2. Δv_1 as a function of y for $(\Delta q,\, \Delta S) = (0,\, 0),\, (4/3,\, 2)$ in Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ GeV in 10%-40% centrality.

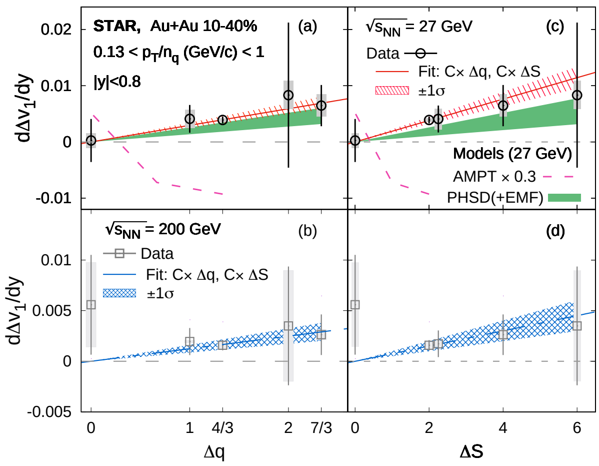

Fig. 3. Δv_1-slope ($d\Delta v_1/dy$) as a function of Δq, and ΔS for 10%-40% centrality in Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ GeV and $\sqrt{s_{\rm NN}} = 27$ GeV.

In Fig. 3, we display the mid-rapidity Δv_1-slope ($d\Delta v_1/dy$) as a function of Δq and ΔS for 10%-40% central Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ and 200 GeV. The $d\Delta v_1/dy$ increases with Δq and ΔS. The slope parameters of the $d\Delta v_1/dy$ with Δq, $d^2\Delta v_1/dy\, d\Delta q$, are $[2.952 \pm 0.489$ (stat.) ± 0.367 (syst.)$] \times$

10^{-3} and $[1.242 \pm 0.381\ \text{(stat.)} \pm 0.258\ \text{(syst.)}] \times 10^{-3}$ at $\sqrt{s_{\rm NN}} = 27$ and 200 GeV, respectively. The magnitude of the Δv_1 slope is larger at $\sqrt{s_{\rm NN}} = 27$ GeV than at 200 GeV with 4.83σ significance. The AMPT calculations [10, 11] do not agree with the measurements whereas the PHSD with EM field calculations can explain the data within uncertainties. The PHSD model with EM field assumes that all electric charges are affected by the strong EM field which ensures splitting of v_1 between positive and negative particles as observed in Fig 3.

4. Summary

In summary, we present the first measurements of directed flow, $v_1(y)$, of Ξ and Ω in Au+Au collisions at $\sqrt{s_{\rm NN}} = 27$ GeV and 200 GeV. There is a hint of a relatively larger v_1-slope for Ω^- compared to the Ξ baryons within the uncertainties. We measure directed flow splitting, Δv_1, with Δq and ΔS. The Δv_1-slope for hadron combinations, increases with Δq and ΔS. The strength of the splitting increases going from $\sqrt{s_{\rm NN}} = 200$ to 27 GeV. The PHSD with EM field calculations can describe the Δq and ΔS dependent splitting within uncertainties.

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